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Feasibility study of wind energy potential for electricity generation in the northwestern coast of Senegal

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Abstract

The aim of this paper is to determine the wind energy potential for electricity generation in the northwestern coast of Senegal. The wind characteristics and wind energy potential in eight sites (Kayar, Potou, Gandon, Sakhor, Sine Moussa Abdou, Botla, Dara Andal and Nguebeul) are analyzed using the wind speed data collected during a period of one year for each site. The annual mean wind speed and the power density were computed. Results obtained show that the annual mean wind speed varies between 5.28 m/s in Potou (at 30 m) and 3.10 m/s in Dara Andal (at 7 m). The corresponding power density varies between 120.01W/m² and 30.05 W/m² respectively.

A technical assessment of electricity generation from three big wind turbines and from three small wind turbines was carried out. Results show that the highest capacity factor was 39% observed in Sokhar for the wind turbine Yellow-Sand, whereas the lowest capacity factor was 5% in Gandon for the wind turbine Ecotecnia 80. The highest output energy was 4,517,900k Wh/year in Sokhar for the wind turbine Repower, while the lowest output energy was 312 kWh/year observed in Gandon for the wind turbine Inclin 600.

Keywords: Feasibility study, Wind Energy, Power density, Electricity generation, Senegal;

1. Introduction

The use of fossil fuels have been creating serious environmental problems, such as gas emissions, air pollution and climate changes thereby making current energy trends to be unsustainable thus necessitating a better balance between energy, economics, development and protection of the environment [1]. Renewable energy sources (wind, solar, hydro, biomass etc.) are inexhaustible, clean,

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free and offer many environmental and economical benefits in contrast to conventional energy sources [2].

Hence, wind energy appears as a clean and good solution to cope with a great part of this energy demand [3].

Recently, many researchers [4, 5, 6, 7] have studied the wind energy resources for electricity generation in sites all over the world. In Senegal, the development of new wind projects continues to be hampered by the lack of knowledge of wind potential and the absence of reliable and accurate wind resource data in many parts of the country.

Recent studies [8-17] have concluded that the best area to use wind energy was along the coastal areas of Senegal.

Other works [12-14] for evaluation of wind potential on the northwest coast of Senegal are made. The results of these studies have shown the importance of the available wind potential and that this potential varies with the period during the day and also varies from one season to another. However, a feasibility study for a wind project in this area is necessary.

The contribution of this paper is to assess the wind power potential in eight sites (Kayar, Potou, Gandon, Sakhor, Sine Moussa Abdou, Botla, Dara Anda and Nguebeul) located in the northern coastal of Senegal and to assess the wind electricity generation by using three big wind turbines which the nominal power is between 1250 kW and 2000 kW and three other small wind turbines which the nominal power varies between 0.3 W and 0.6 kW.

2. Materials and methods

2.1. Description of the sites and collected data

In this study, eight metrological stations were installed in the sites of Kayar, Potou, Gandon, Sakhor, Sine Moussa Abdou, Botla, Dara Andal and Nguebeul (Fig.1) located along the northwestern coast of Senegal. The site of Sakhor is far from the sea but the presence of hallway coming from the sea can promote the acceleration of the wind speed, increasing thus the regular wind speed. These stations were equipped with a data acquisition system which, records every 10 min the average, maximum and minimum values for each sensor. The data are saved in a flash memory card. The evaluation of the collected data in the sites has showed that the coverage rate was between 82 % and 100 %. The minimum value (82 %) was observed for the site of Nguebeul. The coverage rate value is very high in generally and allows the use of these data in order to calculate the wind potential for the sites. Table 1 gives the locations of meteorological stations, period of collect and the coverage rate of data for each site.

Table 1. Characteristics of the eight meteorological stations

Site	Latitude north (°)	Longitude west (°)	Elevation (m)	Measures period	Coverage rate (%)
Kayar	14.92	17.12	06.00	August 2007 to July 2008	100
Potou	15.72	16.50	21.00	August 2007 to July 2008	100
Gondon	15.96	16.45	05.00	Jun 2004 to May 2005	99
Sine Moussa	15.18	16.74	54.00	November 2007 to October 2008	95
Botla	15.67	16.49	28.00	November 2007 to October 2008	94
Dara Andal	15.42	16.53	43.00	November 2007 to October 2008	86
Ngeubeul	15.35	16.59	51.00	November 2007 to October 2008	82
Sakhor	14.23	16.45	03.00	November 2007 to October 2008	96

Fig.1. Localization of the eight sites used in this study located along the northwestern coast of Senegal

2.2. Theoretical models

2.2.1. Mean wind speed

In the present study, the wind speeds data measured every ten minutes for one year in each site were used to calculate the wind potential. The monthly and annual mean wind speed values were calculated by using Eq (1) [18].

$$v_m = \frac{1}{n} \cdot \sum_{i=1}^{n} v_i \tag{1}$$

Where n is the observation number and v_i is the wind speed in time stage i.

2.2.2. Weibull distribution

Weibull distribution has been commonly used in literature to express the wind speed distribution and to estimate the wind power density. The Weibull distribution is a good match with the experimental data [13,19]. It is given by Eq (2) [20].

Where A and k are respectively the scale and the shape parameters of Weibull [21, 12-14].

$$f(v) = \frac{k}{A} \cdot \left(\frac{v}{A}\right)^{k-1} \exp\left(-\left(\frac{v}{A}\right)^{k}\right) \tag{2}$$

2.2.3. Wind power density

The calculation of the wind power density is an important in assessing wind power projects. According to [1, 22, 23], the wind power is expressed by Eq (3).

$$P(v) = \frac{1}{2} \cdot \rho \cdot S \cdot v^3 \quad (3)$$

While the power density (the power of the wind per unit area) is given as Eq (4).

$$p(v) = \frac{P(v)}{S} = \frac{1}{2} \cdot \rho \cdot v^3 \quad (4)$$

ρ is the air density (1.225 kg/m3), S is the sweep area of the rotor blades (m2).

The long-term wind speed distribution f (v) is combined with the available wind power to give the average wind power density, which can be expressed by Eq (5) [24] based on the Weibull probability density function.

$$p(v) = \frac{1}{2} \cdot \rho \cdot A^3 \cdot \Gamma\left(1 + \frac{3}{k}\right) \quad (5)$$

Where Γ(x) is the gamma function of (x).

2.2.4. Extrapolation of wind speed with height

The wind speed was collected in the sites at two heights above ground level. For wind projects, it is necessary to estimate the wind speed at the wind turbine hub height. According to the literature [12-14, 19], the most commonly used method to adjust the wind speed from one level to another is the power law method [25] expressed by Eq (6).

$$v = v_0 \cdot \left(\frac{h}{h_0}\right)^{\alpha} \quad (6)$$

Where v_0 is the reference wind speed (m/s), h_0 is the reference height (m), v is the wind speed (m/s) to be determined for the desired height h and α is the roughness factor estimated by using the wind speed measurement at the two altitudes, in our case study h_0=20 m.

2.3. *Wind turbine output model*

Major wind turbine manufacturers give the power curves of their products in their technical notes. So, it is simple to estimate the power output of any wind turbine when a series of measurements were conducted in the studied site. However, in several cases, only the probability distribution function is available. In this situation the power output of the wind turbine can be expressed by Eq(7) [26].

$$P_{w,\,avg} = \int_0^{+\infty} P_w \cdot f(v) \cdot dv \quad (7)$$

Where f(v) is the Weibull distribution given by Eq(2), P_w is the electrical power ouput of the turbine.

The average energy output E_{out} for a period of time will be calculated as Eq (8).

$$E_{out} = P_{w,avg} \cdot \Delta t \quad (8)$$

Where Δt is the time period. For the annual wind energy estimation, the value of 8,760 hours is used.

The capacity factor C_f is one of the performance parameters of wind turbines that both the user and manufacturer need to know. It represents the fraction of the total energy delivered over a period (E_{out}) divided by the maximum energy that could have been delivered if the wind turbine was used at maximum capacity over the all period [13, 14, 21].

3. Results and discussion

3.1. Annual mean wind potential along northwestern coast

The collected data over the period of one year for the eight selected sites, located in northwestern of Senegal, were used to calculate the wind potential. The annual mean wind speed was calculated by using the Eq. (1).

3.2. Wind regimes along he northwestern coast

The variation of the monthly mean wind speed and power density was determined by using the collected data at 20 m of high in Kayar, Potou and Gandon and with the use of the data measured at 12 m in Sakhor, Sine Moussa Abdou, Botla, Dara Andal and Nguebeul. Tables 3 and 4 give the results obtained.

From Table 2, it can be noted that the highest monthly mean wind speed during the period of the year was determined as 4.95 m/s 5.29 m/s in May for Kayar and Sakhor and as 5.40 m/s, 4.91 m/s, 5.19 m/s, 4.94 m/s, 5.08 m/s and 5.32 m/s observed in April for the sites of Potou, Gandon, Sine Moussa Abdoul, Botla, Dara Andal and Nguebeul. The lowest monthly mean wind speed is equal to 3.29 m/s, 3.57 m/s, 3.64 m/s; 3.05 m/s, 3.18 m/s, 3.07 m/s and 3, 61 m/s observed in September for the sites of Kayar; Potou Gandon, Sine Moussa Abdou, Botla, Dara Andal and Nguebeul and equal to 3.09 m/s observed in October for Sakhor.

Table 3 depicts the monthly mean power densities computed on the eight sites. The highest power density was 98.43 W/m² and 136.89 observed in May for Kayar an Sakhor and was 133.53 W/m², 89.69 W/m², 134.35 W/m², 115.61 W/m², 110.28W/m² and 125.22 W/m² observed in April for the sites: Potou, Gandon, Sine Moussa Abdoul, Botla, Dara Andal and Nguebeul. The lowest power density was 38.74 W/m², 44.34 W/m²; 49.79 W/m², 35.05 W/m²; 36.50 W/m², 29.35 W/m² and 41.12 W/m² in September for Kayar, Potou, Gandon, Sine Moussa Abdou, Botla, Dara Anda, Nguebeul and was 32.38 W/m² in October for the site of Sakhor. In general, the monthly mean power density over the all sites remains greater than 29 W/m² in the all sites (Table 3). That allows the electricity generation using adapted wind turbine.

The statistical analysis of wind speeds has been carried out through determining the distribution and the parameters of Weibull. The observed and the Weibull distribution were also determined. Figure 2 and figure 3 show a good corresponding between the observed and the theatrical distribution (Weibull distribution). This study, also, made it possible to determine the monthly Weibull parameters for the all sites. The table 4 depicts the results of scale and shape parameters obtained for the all sites.

It can be noted that the monthly mean scale parameter is between 3.72-5.32 m/s, 4.03-5.88 m/s, 4.09- 6.33 m/s for Kayar Potou and Gandon. It varies between 3.49 - 5.74 m/s, 3.43-5.99m/s, 3.59-5.56m/s, 3.47-5.67, m/s and 4.04-5.94m/s for the sites of Sakhor, Sine Moussa Abdou, Botla, Dara Andal and Nguebeul respectively.

The values of the scale parameters over the all sites show that the wind potential can be used to produce electricity from wind turbines. However, using an adapted wind turbine for electricity generation is necessary.

The shape parameter observed (Table 4) was between 2.17-3.37, 2.88-3.62, 2.26-3.59 for Kayar, Potou and Gandon. It was between 1.91-2.84, 1.89-3.28, 2.06-2.87, 2.22-3.30 and 2.58-3.40 for the sites of Sakhor; Sine Moussa Abdou, Botla, Dara Andal and Nguebeul respectively. The highest value of the shape parameter was 3.62 observed in Potou (January) whereas the lowest value was 1.89 observed in Sine Moussa Abdou (August). There for, the wind speed is most uniform in Potou in January and least uniform in Sine Moussa Abdou in August due to obstacles which cause more wind disturbance in the site Sine Moussa Abdou compared to site of Potou.

The scale and the shape parameters were, also, computed at the highs hub of the wind turbines and were used to estimate the output energy and capacity factor from these wind turbines.

3.3. Estimation of energy output and capacity factor

3.3.1. Wind turbines characteristics

Table 5 shows the features of the selected wind turbines from several manufactures [27]. The rated power of these wind turbines is between 1250 and 2000 kW for the large wind turbine and varies between 300 W and 600 kW for the small wind turbines.

For the large wind turbine, the Cut-in speed varies between 3 - 4 m/s and the rated speed is between 13-14.50 m/s in contrast for the small wind turbines, the cut-in speed varies between 2-3.5 m/s and the rated speed is between 8-11 m/s. These wind turbines were used to study their performance by calculating the output energy and the capacity factor in the all sites so as to choose the suitable wind turbine for electricity generation to connect to the network or for isolated application.

3.3.2. Wind turbine energy output and capacity factor

The annual output energy and the capacity factor of large and small different wind turbines for the eight stations were calculated. The results obtained are given in Tables 6 and 7.

Table 6 depicts the capacity factors of the wind turbines. It can be noted that the highest capacity factor is obtained in the site of Sakhor for the all used wind turbines. The value was between 19% (Inclin-600) and 39% (Yellow-Sand) in contrast in the site of Gandon, the capacity factor was lowest, and it varies between 5 % and 18 % for Ecotècnia 80 and Yellow-Sand respectively. It can be noted, also, that the capacity factor is highest for the wind turbine Yellow-Sand in the all site and lowest for the wind turbine Ecotècnia 80 over the sites. That is because of the wind turbine Yellow-Sand has the lowest nominal speed in contrast of the Ecotècnia 80 has a greater nominal speed. In general the capacity factor is greater for the wind turbines which the nominal speed is lower. This remark was observed in the one hand for the large wind turbines and on the other hand for the small wind turbines.

Table 2. Monthly mean wind speed (m/s) on the sites

Site	Kayar at 20m	Potou at 20m	Gandon at 20m	Sakhor at 12m	Sine Moussa at 12m	Botla at 12m	Dara Anda at 12m	Nguebeul at 12m
January	4.63	5.25	4.57	5.00	5.19	4.42	4.10	4.20
February	4.75	5.09	4.68	5.04	4.74	4.18	4.05	4.25
March	4.07	5.05	4.57	4.92	4.83	4.48	4.41	4.82
April	4.46	5.40	4.91	5.10	5.34	4.94	5.08	5.32
May	4.91	5.30	4.69	5.29	5.13	4.83	4.85	5.02
Jun	4.32	5.04	4.44	5.00	4.89	4.58	4.89	4.89
July	4.30	4.57	4.41	4.40	4.21	4.10	4.36	4.46
August	3.95	4.33	4.11	3.80	3.61	3.61	4.00	4.08
September	3.29	3.57	3.64	3.13	3.05	3.18	3.07	3.61
October	4.10	4.42	3.85	3.09	3.42	3.43	3.58	3.73
November	4.60	4.65	4.23	4.12	4.37	3.89	3.59	3.80
Décember	4.43	4.88	4.01	4.49	4.54	3.96	3.75	3.81

Table 3. Monthly mean power density (W/m²) on the sites

Site	Kayar at 20m	Potou at 20m	Gandon at 20m	Sakhor at 12m	Sine Moussa at 12m	Botla at 12m	Dara Anda at 12m	Nguebeul at 12m
January	90.97	112.45	81.7	110.07	101.00	89.84	70.08	67.80
February	92.82	107.59	80.22	108.94	91.75	75.51	60.62	65.91
March	55.79	109.64	75.26	116.68	101.87	97.11	70.78	96.12
April	71.57	133.53	89.69	129.47	134.35	115.61	110.28	125.22
May	98.43	117.36	81.86	136.89	110.31	99.26	93.42	102.03
Jun	68.89	106.48	80.00	123.68	112.55	94.62	103.95	103.95
July	73.1	84.55	76.27	84.69	77.35	72.48	74.30	76.84
August	56.37	72.41	62.95	60.23	57.73	52.42	47.70	60.67
September	38.7	44.3	49.79	38.08	35.05	36.50	29.35	41.12
October	57.99	72.09	52.31	32.38	44.00	42.05	36.17	46.57
November	84.55	85.13	62.74	73.02	84.37	66.45	49.51	51.90
December	77.13	91.33	52.63	85.7	84.75	64.26	50.51	47.44

Table 4. Monthly scale parameters A (m/s) and shape parameter for the sites

Month		Kayar at 20m	Potou at 20m	Gandon at 20m	Sakhor at 12m	Sine Moussa at 12m	Botla at 12m	Dara Anda at 12m	Nguebeul at 12m
January	A(m/s)	5.21	5.80	5.11	5.60	5.85	5.01	4.64	4.73
	k (-)	2.70	3.62	3.00	2.84	2.74	2.30	2.37	2.73
February	A(m/s)	5.32	5.67	5.18	5.64	5.31	4.74	4.56	4.76
	k (-)	2.95	3.33	3.59	3.04	3.00	2.32	2.75	3.03
March	A(m/s)	4.54	5.66	5.06	5.54	5.43	5.07	4.97	5.4
	k (-)	3.19	3.08	3.52	2.45	2.78	2.25	2.66	3.03
April	A(m/s)	4.96	6.04	5.42	5.74	5.99	5.56	5.67	5.94
	k (-)	3.37	3.08	4.01	2.45	2.87	2.51	3.11	3.02
May	A(m/s)	5.48	5.88	5.2	5.95	5.71	5.42	5.41	5.59
	k (-)	3.18	3.58	3.45	2.65	3.28	2.87	3.30	3.40
Jun	A(m/s)	4.83	5.63	5.00	5.64	5.51	5.16	5.49	5.49
	k (-)	3.00	3.20	3.27	2.43	2.50	2.42	2.84	2.84
July	A(m/s)	4.83	5.12	4.95	4.97	4.75	4.61	4.89	5.00
	k (-)	2.67	2.84	2.82	2.42	2.28	2.22	2.79	2.96
August	A(m/s)	4.44	4.87	4.61	4.31	4.06	4.07	4.06	4.59
	k (-)	2.71	2.83	2.70	2.16	1.89	2.10	2.31	2.86
September	A(m/s)	3.72	4.03	4.09	3.54	3.43	3.59	3.47	4.04
	k (-)	2.17	2.48	2.26	1.91	1.89	2.06	2.35	2.89
October	A(m/s)	4.58	4.94	4.32	3.49	3.85	3.88	3.74	4.20
	k (-)	3.12	3.17	2.28	2.14	2.11	2.28	2.41	2.82
November	A(m/s)	5.15	5.19	4.71	4.65	4.93	4.40	4.06	4.28
	k (-)	2.93	3.05	3.18	2.27	2.36	2.09	2.22	2.58
December	A(m/s)	4.97	5.41	4.47	5.06	5.11	4.48	4.23	4.27
	k (-)	2.85	3.57	3.31	2.57	2.75	2.30	2.53	3.02
All data	A(m/s)	4.84	5.35	4.84	5.01	4.99	4.67	4.60	4.86
	k (-)	2.90	3.15	3.12	2.44	2.54	2.31	2.64	2.93

Table 5. Characteristics of three large and three small commercial wind turbines from several manufactures

Description of wind turbine	Rated power Pr (kW)	Sept area S (m²)	Cut-in wind speed Vci (m/s)	Rated wind Speed Vr (m/s)	Cut-off wind Speed Vco (m/s)	Hub height (m)
Large Wind Turbine						
Ecotècnia 62	1250	3019	3	13.5	25	60
Ecotècnia 80	1670	5027	3	14	25	70
Repower	2000	5278	4	13	25	100
Small Wind Turbine						
EolSenegal 500	0.5	7.06	2	9	12	18
Inclin 600	0.600	3.14	3.5	11	13	7
Yellow Sand	0.300	4.52	3	8	15	12

Table 7 shows the output energy from the all wind turbines used for this study. It can be noted that the output energy is greater for the site of Sakhar than for the other sites. Because of the size of wind turbines, the output energy is greater for the large wind turbine than for the small wind turbine over the all sites. Indeed, for the large wind turbine, the output energy varies between 750,360 kWh/year (for Ecotècnia 80) in Gandon and 4,517,900 kWh/year (for Repower) in Sakhor whereas for the small wind turbine, the output energy varies between 312 kWh/year (for Inclin-600) and 1,470 kWh/year (for EolSenegal) in the same sites respectively.

For an electricity application, we have to choose wind turbines with output energy and capacity factor which is greater. So, the wind turbine Repower is suitable for the generation electricity for grid connection, because of the quantity of output energy that could be generate in contrast the Yellow-Sand is better for the isolated application because of the high capacity factor. So the wind turbine could operate for more time given the maximum of his nominal capacity. That could be interesting for the isolated application because of, for the rural electric using renewable energy application; it is very important to have energy every time to serve the demand.

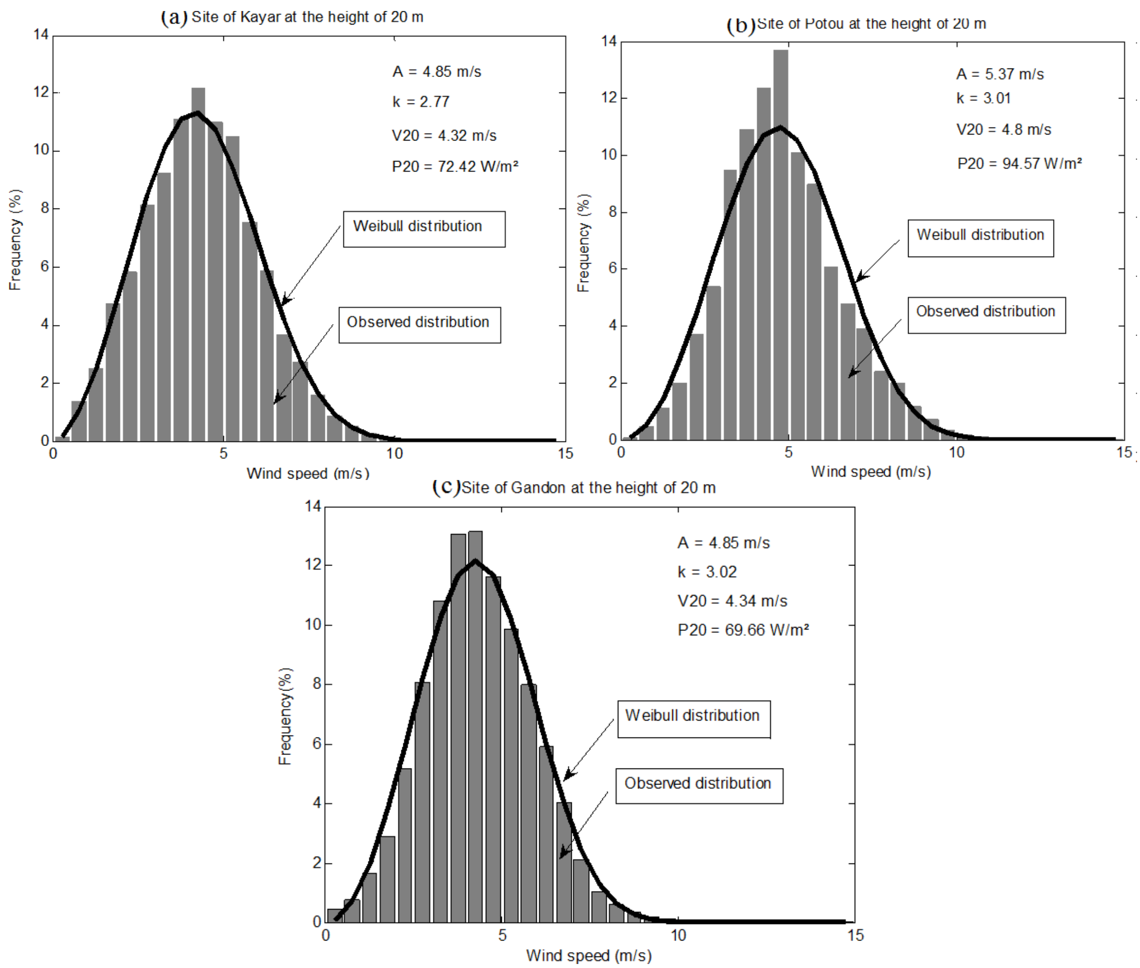

Fig. 2. Weibull and observed distribution in sites (a) Kayar, (b) Potou and (c) Gandon

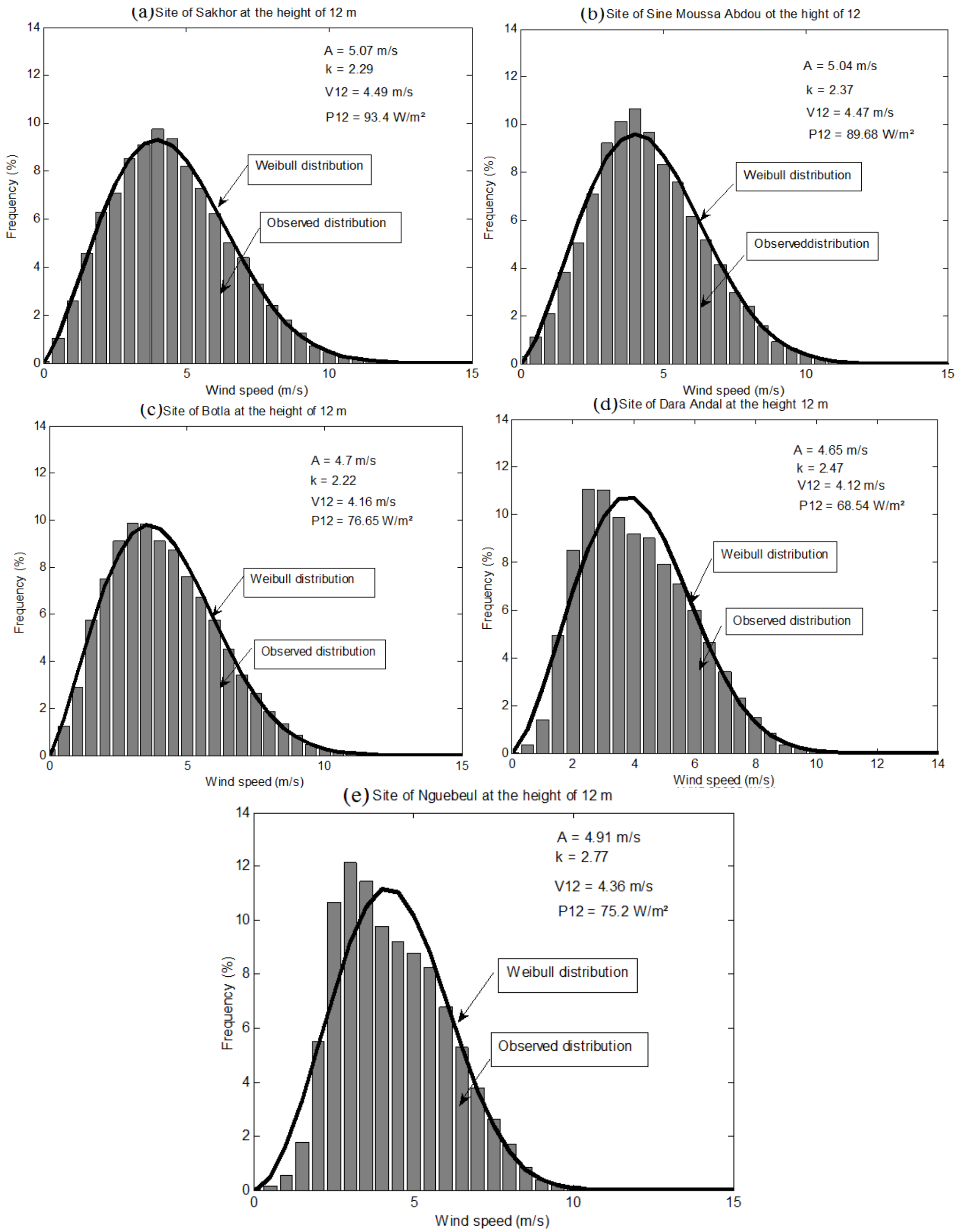

Fig. 3. Weibull and observed distribution the sites :(a) Sakhor, (b) Sine Moussa abdou, (c) Botla, (d) Dara Andal and (e) Nguebeul

Table 6. Yearly capacity factor (%) of the fifteen different commercial wind turbines in the all sites

Type of Wind Turbine	Kayar	Potou	Gandon	Sakhor	Sine Moussa Abdou	Botla	Dara Anda	Nguebeul
Large Wid Turbine								
Ecotècnia 62	8	15	6	26	22	19	19	14
Ecotècnia 80	7	14	5	24	21	17	17	13
Repower	8	15	6	26	22	19	19	14
Small Wind Turbine								
EolSenegal 500	17	30	14	34	32	28	27	25
Inclin 600	7	17	6	19	18	15	14	12
Yellow Sand	20	33	18	39	37	32	31	30

Table 7. Yearly output energy (kWh/year) of the fifteen different commercial wind turbines in the all sites

Type of Wind Turbine	Kayar	Potou	Gandon	Sakhor	Sine Moussa Abdou	Botla	Dara Anda	Nguebeul
Large Wind Turbine								
Ecotècnia 62	841,490	1,618 000	636,020	2,815,400	2,450,600	2,088,800	2,035,000	1,525,200
Ecotècnia 80	10,08,600	1, 977,700	750,360	3,484,100	3,016,100	2,554,500	2,509,800	1,841,000
Repower	1,279,500	2,498,600	1,000,900	4,517,900	3,920,000	3,335,000	3,152,200	2,444,600
Small Wind turbine								
EolSenegal 500	733	1,296	634	1,470	1,391	1,231	1,180	1, 088
Inclin 600	379	871	312	1,012	925	789	726	635
Yellow Sand	527	856	474	1, 015	966	831	826	798

4. Conclusion

The aim of this paper was to evaluate the wind potential for electricity generation by using one year of wind collected data each ten minutes in eight sites located in the northwestern coast of Senegal.

The wind speed and the wind power density were determined for the period of a year in Kayar, Potou, Gandon, Sakhor, Sine Moussa Abdou, Botla, Dara Andal and Nguebeul.

The wind speed distribution of locations was found by using Weibull distribution functions. From this statistical data and calculations of electricity generation, it can conclude that:

The wind potential is very important with the annual mean wind speed obtained as 4.80 m/s, 4.32 m/s, 4.34 m/s in the sites of Potou, Kayar, Gandon at the height of 20 m. It was 4.49 m/s, 4.47, 4.16 m/s, 4.12 m/s and 4.36 m/s in the site of Sakhor, Sine Moussa Abdou, Botla, Dara Andal and Nguebeul at the height of 12 m. The corresponding power density was 94.57 W/m², 72.42 W/m², 69.66 W/m², 91.65W/m², 86.26 W/m², 75.51 W/m², 66.39 W/m² and 73.80 W/m² respectively.

The performance study of the all wind turbines was achieved in the all sites through determining the factor capacity and the output energy. The all wind turbines had the best capacity factor in the site of Sakhor. The energy produced was between 750,300 kWh/year (for Ecotècnia 80) in Gandon and 4,517,900 kWh/year (for Repower) in Sakhor whereas for the small wind turbine, the output energy was between 312 kWh/year (for Inclin 600) and 1470 kWh/year (EOLSenegal) in the sites of Gandon and Sakhor respectively.

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